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A PRELIMINARY STUDY OF THE ORIFICE FLOW CHARACTERISTICS OF LN_2 AND LH_2 DISCHARGING INTO A VACUUM

by

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ABSTRACT

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The storage and handling of liquid propellants on board vehicles in space presents many problems. Flow characteristics of the propellants through holes made in the tank walls by meteriod puncture is one such problem and is the subject of this work. Overall discharge coefficients for small-diameter, thick-plate orifices were determined as a function of discharge pressure using liquid nitrogen and liquid hydrogen. Discharge pressures from 3 mm Hg to slightly above the triple point were investigated.

Flow characteristics appear to be sensitive to discharge pressure and the condition of the liquid upstream of the orifice. The condition of the liquid was, of course, dependent on the heat transfer to the containing vessel. A marked difference in flow pattern was observed that depended on whether the liquid was nearly saturated or if two phase flow existed. If the liquid was nearly saturated and no gas phase passed through the orifice the flow could be very nearly predicted by the adiabatic, incompressible flow equations. When gas phase was present upstream of the orifice it appeared that solid formation could take place in the orifice itself and thereby retard the flow.

In addition to the orifice discharge coefficients, a general discussion of observed flow patterns is presented. Author

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Introduction

Successful space exploration depends, among other things, upon the ability to store propellants on board the vehicle for long periods of time. There are many problems and uncertainties associated with the storage and handling of propellants in environments at pressures below their triple points. One such problem is propellant loss caused by meteroid puncture. According to Jazwinski (1) propellant loss prediction can be divided into four distinct areas, namely "(a) properties of the meteroid environment which the vehicle traverses, (b) the penetration process whereby holes are produced in the vehicle, (c) flow relations for the escaping fuel, and (d) probabilistic evaluation of the fuel losses." It is with the problem of flow relations for the escaping propellant that the present work is concerned.

Information on orifice discharge coefficients can be obtained from the literature in large quantities. ASME has specified a standard orifice plate geometry (2) for which flow coefficients have been tabulated. The tabulation is for orifices much larger than the holes produced by meteroid puncture, however. Small diameter orifices are much less predictable than larger ones. Grace and Lapple (3) found that thick-plate orifices failed to give reproducible results at low Reynolds Numbers, even with calibration. A 1/32 inch diameter orifice with 1/32 inch throat length gave a spread of as much as 30 percent in the discharge coefficient for a given Reynolds Number. The range of Reynolds Numbers tested was 10^2 to 10^4.

Thrasher and Binder (4) tested orifices down to 0.15 inch in diameter and with thickness varying from 0.005 to 0.060 inches. They observed a very bad scattering of data for the 0.060 inch thick orifice, verifying the observations of Grace and Lapple for thick orifices. They also observed that the flow coefficient was 10 to 15 percent higher than for thin orifices. Grace and Lapple also observed these higher values for thick orifices.

The discharge coefficients given by Grace and Lapple and by Thrasher and Binder were measured with the area downstream of the orifice flooded with the fluid. This condition will not be present in space. None of the investigators were observing flow into an environment in which the fluid would solidify.

To precisely determine the flow relations that will exist in space, a complete duplication of the environment would be desirable. This duplication is not possible for the type of tests needed. For example, the zero gravity condition cannot, at present, be duplicated for a sufficient length of time to make flow measurements.

In the present work it was possible to observe and measure flow through small diameter orifices into an environment near or below the triple point of the fluid under study. Two fluids were used, namely liquid hydrogen and liquid nitrogen. Liquid hydrogen was used because it will be used as a fuel on certain missiles. Liquid nitrogen was used because it is an inexpensive fluid and presents no particular personnel hazards. The two fluids also give more data to aid in evaluating flow characteristics. Liquid oxygen would be a logical choice for flow measurement, but it was impossible to include it in this work because the triple point pressure is too low and the vacuum pump used was oil lubricated.

The information presented includes orifice discharge coefficients as a function of discharge pressure, general observations of the solid formation when the discharge pressure was below the triple point, and observations of solid formation in the orifice.

THEORY

Two theories have been proposed to predict flow of a saturated or nearly saturated liquid through an orifice, namely an equilibrium flow theory and a metastable flow theory. In the equilibrium model "it was assumed that the vapor bubbles formed throughout the stream cross section at the section where the saturation pressure is reached." (5). Experimental measurements of the flow of saturated water have shown that the mass flow rates are considerably higher than predicted by calculations based on the equilibrium theory. Surface tension effects have been used to explain the variance between the experimental results and the predicted values. It is postulated that vapor bubble formation is retarded because of the surface tension.

In the metastable flow theory it is assumed that vapor bubbles form only on the liquid stream surface. No vapor bubbles form in the orifice when saturated liquid flows through. If, however, some vapor bubbles are present upstream of the orifice and the bubbles flow through with the liquid, the capacity of the orifice is reduced. Benjamin and Miller (6) in some experiments with water, found that the mass flow rate through an orifice was reduced by about 54 percent when steam was passed with the water at the rate of 0.04 lb. of steam/lb. of water with an upstream pressure of 145 psia. As the upstream pressure was decreased the capacity was reduced more severely. At a supply pressure of 75 psia, the reduction was about 65 percent when passing the same amount of steam. In both of these tests the discharge pressure was 15 psia. The change in capacity was also a function of the discharge pressure. As the downstream pressure approached the upstream pressure, the percent change in capacity approached zero.

The metastable flow model appears to apply to the present experiments. The particular pressure ranges investigated and the fluids used are, of course, much different than those used by Bailey or Benjamin and Miller--

the primary difference being that in the present work, downstream pressures below the triple point of the fluid were investigated.

Liquid flowing through the orifice was considered saturated at the barometric pressure. The actual liquid was slightly subcooled -- less than 1 K° for hydrogen and about 1.5 K° for nitrogen. The subcooling was accomplished by rapidly raising the pressure over the liquid. If the liquid came to equilibrium at the higher pressure the density change was less than 1%. Since a finite time was required for the liquid to reach equilibrium at the higher pressure, the error in the density was much less than 1% and was considered negligible.

Discharge coefficients were calculated from the well known relation

$$\mathring{m} = \frac{C_d A \sqrt{2\rho \Delta P}}{\sqrt{1 - \beta^4}} \qquad [1]$$

where

$\mathring{m}$ = mass flow rate

C_d = discharge coefficient

A = area of the throat

ρ = density of the fluid

ΔP = pressure drop across the orifice

β = ratio of orifice diameter to upstream pipe diameter.

The use of this equation implies that several important conditions exist. Some of these are that the flow is incompressible, adiabatic, and unaffected by a change in elevation. For this work it was assumed that equation 1 was valid. Since the largest value of β in these orifices was 0.0294 the quantity $1-\beta^4$ was considered equal to one.

The coefficient of discharge is a composite of several components that affect the flow. Two of these components are the coefficients of contraction and velocity. In this work no attempt was made to evaluate the components separately. According to Prandtl (7) the coefficient of velocity differs considerably from unity for small orifices and low velocities when the ratio of the orifice diameter to the pipe diameter is small. For large openings and high velocities it is usually close to unity.

EXPERIMENTAL APPARATUS

A schematic diagram of the experimental apparatus is shown in figure 1. A glass apparatus was used so that the flow and solid formation could be visually observed. This precluded using high upstream pressures. It was felt, however, that preliminary information where visual observations could be made would aid in understanding the flow patterns and the formation of solids.

A supply dewar of either liquid hydrogen or nitrogen was connected to the transfer line shown on the left in the figure. This liquid was used to fill the measuring volume located inside the six inch glass dewar. The dewar was attached to a six inch pipe that was connected to the inlet of an 1100 cfm vacuum pump. Pressure inside the dewar was regulated manually with a butterfly valve located in the pipe. An absolute mercury manometer was used to measure the pressure inside the dewar.

Pressure over the liquid in the measuring volume was read on a 0-125 cm of Hg abs. Heise gage.

Two different sized measuring volumes were used in the experiments. One had a capacity of 104 ml and the other 312 ml. The size of the vessels was chosen such that tests near the triple point pressure could be completed before the liquid upstream of the orifice started boiling. The actual sizes used were picked by a very rough trial and error process and are not necessarily the best sizes that could have been selected.

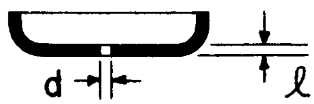
A screen was placed near the bottom of the dewar as a safety measure. If any of the glass measuring volume should happen to break inside the dewar the screen would protect the bottom of the dewar. The tube shown extending through the screen and out the pipe at the top was used to remove the liquid resulting from tests above the triple point or from the melted solid.

A five micron screen was placed upstream of the orifice to filter out any foreign material. This screen was placed in a soldered union approximately two inches above the orifice.

The various valves used for purging and maintaining the pressure above the liquid are shown on the right in the figure.

A mercury manometer, not shown in the figure, was used to measure the barometric pressure.

Orifices were made as shown below by drilling the hole and then lapping the surfaces.



The cupped shape was used so that the orifices could be soldered in place. This eliminated any problems with low temperature joints.

EXPERIMENTAL PROCEDURE

Liquid Nitrogen

Individual orifice plates were thoroughly degreased and washed after lapping. The hole diameter was measured with a micrometer stage microscope and the length measured with a micrometer marked in .0001 inch divisions. The plates were then soft soldered onto a 3/4" O.D. stainless steel tube and cleaned in boiling water. The orifice was then visually checked for cleanliness. A five micron screen was placed in the tube approximately two inches upstream of the orifice to filter the liquid before passing through the orifice. The orifice-tube-screen assembly was soft soldered onto the measuring volume and the glass dewar put in place. The dewar, measuring volume, transfer lines, and pressure lines, were evacuated and purged with nitrogen gas three times to ensure against moisture from the air plugging the orifice. With a vacuum in the dewar space, liquid nitrogen was then admitted into the measuring volume. Liquid was kept in the volume while the dewar was cooled down by the flow out of the orifice.

When the various elements had been cooled sufficiently to prevent vapor bubbles forming in the liquid above the orifice the measuring volume was filled with liquid and the discharge pressure regulated with the butterfly valve. The transfer of liquid was then stopped and the pressure over the liquid in the measuring volume rapidly increased to slightly subcool the liquid.

The flow measurement started when the liquid level in the measuring volume passed the top reference line. At that time a stop watch was started manually. During the course of the run the upstream and downstream pressures were monitored and recorded. The liquid in the phase seperator was also watched for the formation of vapor bubbles. When the liquid level passed a second reference line the stop watch was stopped and the elapsed time was recorded.

The pressure over the liquid was reduced and liquid transfer was started again to fill the volume. Subsequent runs were then made following the same procedure.

When the volume inside the dewar filled with solid to the extent of affecting flow, it was melted and siphoned out through a heat exchanger and vented. After the liquid was removed the dewar was evacuated to the desired operating pressure and the phase separator was again filled with liquid to start another test.

Liquid Hydrogen

After testing with liquid nitrogen was completed, the nitrogen was removed from the dewar. The whole apparatus was evacuated and purged with hydrogen three times. Actual measurements with liquid hydrogen were made following the same procedures used in testing with liquid nitrogen.

When all measurements had been made with liquid hydrogen the dewar was pressurized and all the liquid removed. The apparatus was then evacuated and purged with nitrogen at least three times and then tested with a portable combustible gas analyzer.

At the completion of all the tests on an orifice the dewar was removed and the components warmed to room temperature. A new orifice was then placed on the apparatus in place of the one just tested. Then the procedure was repeated with the new orifice.

RESULTS

Orifice discharge coefficients for liquid nitrogen are shown in figure 2 and for liquid hydrogen in figure 3. The triple point pressures for both liquids are shown by the dashed vertical line on the respective curves. No discontinuity in the discharge coefficient appeared as the downstream pressure was raised or lowered through the triple point pressure.

The solid black data points indicate tests in which the solid formation built up into the orifice. No attempt was made to ascertain the actual time the solid was in contact with the orifice. As it turned out, however, no difference could be noticed between runs made with solid in contact with the orifice for the entire run or for just a short duration.

The curves were fitted to the points by eye and are all parallel for a given liquid. Points at higher discharge pressures were not obtained because the liquid would start boiling before a test could be completed. Only tests completed without boiling are included in the two figures.

Some additional tests were performed with liquid nitrogen flowing through an orifice with a hole diameter of 0.0103 inch and a thickness of 0.016 inch. With a discharge pressure of 3 mm Hg. and an upstream pressure of 665 mm Hg. a coefficient of discharge of 0.622 ± 0.004 was obtained in a total of eight tests. Discharge coefficients at higher discharge pressures and with liquid hydrogen as the test fluid were not obtained because of vaporization upstream of the orifice.

DISCUSSION

The discharge coefficients were calculated using equation 1 with density values taken from Strobridge (8) for liquid nitrogen and from Goodwin et al. (9) for liquid hydrogen. As mentioned before the density was taken at saturation at the barometric pressure. Since only a slight amount of subcooling was used and this was done by a rapid pressurization the error introduced was negligible.

Since the fluid flowing through the orifice was considered to be in a metastable condition the values of the discharge coefficients are not surprising. In fact they compare within experimental accuracy with measurements made on larger orifices by Richards, et al. (10) with the same two fluids under conditions in which the liquid was in equilibrium both upstream and downstream of the orifice. There was a rather large scattering of the data in Richards' work, however, Most discharge coefficients published are presented as a function of Reynolds Number. In the tests reported here the Reynolds Number obtained with liquid nitrogen was approximately 3×10^4 and with liquid hydrogen it was approximately 10^5 and did not change sufficiently to permit this type presentation. Therefore, a good comparison with other work cannot be made since the data included in this paper would cover a very small range in most papers. Within this limitation the values obtained compare favorably.

The different slopes on the curves for nitrogen and hydrogen are due to the difference in velocities. When discharge coefficients are plotted against Reynolds Number it is found that the coefficient rises to a maximum in the viscous flow region and then decreases to a rather constant value as the Reynolds Number increases. Figure 4, from Tuve and Sprenkle (11), shows this effect for two different diameter ratios.

Variation of the experimental points was not considered too severe for the type test conducted. All the points lie within 4 percent of the curve drawn to represent them. The variation between different tests was largely due to experimental error in the time and pressure measurements. The errors in the time measurement would be most important since pressure enters the calculation to the 1/2 power and time enters to the first power. In this respect, longer runs would have been advantageous in order to reduce the effect of these errors. This advantage had to be compromised, however, in order to allow all the tests to be completed before vaporization started upstream at the orifice.

Pressure measurements for determining orifice flow are supposed to be taken at specified locations both upstream and downstream of the orifice. These locations were not adhered to in these experiments for two reasons. The first reason was that any kind of a pressure tap located in the stream at the discharge of the orifice would upset the flow pattern. When the discharge pressure was below the triple point solid would collect on any pressure tap and build up onto the orifice. No side taps could be placed in a tube wall at the exit of the orifice because the orifice was not in a tube. The orifice was not located inside a pipe because it was desired to simulate the flow characteristics of a meteroid puncture of a propellant tank. If the orifice was placed in a small diameter pipe the solid nitrogen or hydrogen would collect on the wall and restrict the flow. Large diameter pipes would not provide much better pressure measurements than were obtained with the existing apparatus. The actual size of the exit pipes where flow restrictions become a problem is not known. It was considered beyond the scope of this investigation to determine the effect of exit tube diameters.

The second reason for not making pressure measurements at the standard locations was because the information desired was related to bulk tank pressures and exit pressures. Therefore, even if it was possible to place pressure taps at given locations the over-all bulk pressure drop would still be the most important parameter in predicting propellant losses.

It was also planned to test orifices with a 0.010 in. diameter hole. When these tests were performed it was very difficult to prevent the liquid from boiling upstream of the orifices. The combined effect of heat transfer into the apparatus and the mass flow through the orifice was such that vaporization usually started before a test could be completed. Several efforts were made to test one orifice with a 0.0103 in. hole. At the lowest discharge pressure obtainable it was possible to run tests with liquid nitrogen. If the discharge pressure was raised, the liquid would immediately start boiling and some gas phase would start flowing through the orifice. Efforts to suppress the boiling by slightly subcooling the liquid by pressurization at the higher discharge pressures failed. As soon as the discharge pressure was lowered however, the boiling would stop. Consequently a value for the discharge coefficient for this orifice was determined at only the 3 mm Hg. discharge pressure with liquid nitrogen.

When liquid hydrogen was used with the 0.0103 in. diameter orifice, it was impossible to stop the boiling at even the lowest discharge pressure. Solid hydrogen would also form in the orifice during these tests. Flow out of the orifice was intermittent liquid and gas with the formation of solid taking place in the orifice very quickly after flow started. This solid formation would completely encircle the orifice and substantially reduce the flow. A complete plug of the orifice was never observed, however. The solid in the orifice was removed by sublimation after the measuring volume ran out of liquid.

Solid formation in the orifice was also observed in the larger orifices when testing with liquid hydrogen. In these orifices, however, the solid would stop forming when the apparatus got sufficiently cold to reduce or eliminate vaporization upstream of the orifice. During all of the testing, no solid formation at the orifice was observed unless some gas phase was passing through the orifice. The corollary was not true, i. e., whenever gas phase went through the orifice, solid did not necessarily form. There seemed to be a maximum amount of gas that could go through the orifice without forming solid. If more gas was present, then solid would form; otherwise the flow was just intermittent liquid or an atomized mixture of liquid and gas. If, however, the flow was completely gas, for example during the first stages of cool down, there would be no solid formed either. It appeared that both the liquid and the gas phase were required upstream of the orifice in order to produce solid in the orifice.

A possible reason for solid to form as specified above is due to pressure surges across the orifice. As mentioned before, the solid formed during cool down when there was pressure surging throughout the whole apparatus. During these surges it may have been possible for the low pressure to penetrate the orifice sufficiently to cause solidification of some of the liquid.

Location of the solid formation with respect to the orifice under stable running conditions was a definite function of the discharge pressure. At the lowest pressures the exit from the orifice was a jet of liquid about 1/16 inch long. At the end of this jet there was a small region of flashing where the liquid changed to a mixture of solid and vapor. The resulting solid had the appearance of a fluffy snow. When the discharge pressure was increased,the jet of liquid out of the orifice changed abruptly from the 1/16" jet to a much longer jet. The length of the jet was somewhat unpredictable. Sometimes the jet would be about 18 inches long and would form solid only upon striking some other solid material. This flow pattern was always observed at discharge pressures in the region of the triple point pressure. Occasionally, however, the flow pattern would undergo two changes. The first change occurred at discharge pressures intermediate between the triple point pressure and the lowest pressure obtained. The exact pressures where this intermediate flow pattern existed were also not reproducible. The flow pattern that occurred at these intermediate pressures was one in which the liquid jet appeared to fan out in an inverted funnel shape with solid and vapor formation in very small transition region. The solid formed by this flow pattern had the appearance of sleet. As the discharge pressure was increased to values closer to the triple point pressure, the second change in flow pattern took place. This pattern was, as stated before, one in which solid formed only when the liquid jet came into actual contact with something solid.

A probable reason the intermediate flow pattern was unpredictable was because of differences in disturbances from one time to the next caused mainly, perhaps, by vibrations. The fluid was in a metastable state downstream of the orifice. The farther it was from a point of stable equilibrium, the less disturbance it took to make it change to the stable equilibrium state, hence, the short liquid jet at the lowest pressures and the longer jets at the higher pressures as the degree of metastability decreased.

Figure 5 is a photograph of the solid formed at intermediate pressures when the liquid stream did not flash before striking something solid. The formation in the photograph is typical of all those observed under the above conditions. The flow out of the orifice can be seen directly above the solid. It is possible to see that the solid has built right up into the liquid jet from the base which in this case was compacted solid. The solid leaning over to the left had previously built up and fallen over. The solid appeared to have considerable strength and was not too brittle. At times a formation would build up to a height of about 18 inches right into the jet of liquid without falling down. The formation would either continue building up right to the orifice itself or would bend to one side. Figure 6 is a photograph of solid that has built up onto the orifice. The cross sections of these formations were on the order of 3/16 to 1/4 in. diameter with many branches extending out the sides. It looked rather like a leafless tree. At pressures near the triple point the solid was clear like ice but as the pressure was reduced the solid turned white. Figure 7 is a photograph of solid formation at a discharge pressure just below the triple point. The liquid jet is visible to the right of the 1/4 inch tube directly above the solid. Solid formed at this pressure did not build such slender formations as at lower pressures. The solid seemed to form on the lower portions of the formation at the same time new solid was added to the top. Hence, the longer the run the larger the whole formation would get.

The photographs in figures 5, 6, and 7 were taken of nitrogen. They are typical of the two fluids, however, since the formation of solid hydrogen was very similar to nitrogen, the main difference being the different pressures required.

CONCLUSIONS

Orifice discharge coefficients presented in this paper are for a very limited range of orifice diameters. Larger orifices could have been tested but due to the limited volume inside the dewar the solid accumulation would always be a problem. Of more interest perhaps would be smaller sized orifices. There will be smaller sized holes produced by meteroid penetration and the flow characteristics are of considerable importance. Of particular interest is information on whether there is a threshold diameter where solid starts forming in the orifice. However, with the present apparatus it was impossible to test a 0.0103 inch diameter orifice because of liquid boiling.

The information obtained is in a useful size range and shows that nothing drastic happens to the flow that would lead to discrepancies in predicting propellant losses. A variation in the flow pattern was observed as the discharge pressure was lowered. This variation did not effect the discharge coefficient. If another change in flow should take place at even lower discharge pressures, the solid formation could conceivably take place in the orifice. If this should happen the discharge coefficient would probably be affected.

In addition to the discharge coefficients, some general information on solid formation was obtained. This information will be useful in evaluating the effects of solid formation in propellant venting devices, leaking valves etc. on a space vehicle.

There is a need for more information on propellant losses caused by meteroid puncture of the tanks. Future work might include smaller diameter orifices; orifices of different length; lower discharge pressures; and different fluids, in particular, liquid oxygen.

ACKNOWLEDGMENT

The assistance of Willard J. Bell in fabrication and data taking is gratefully acknowledged.

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LIST OF FIGURES

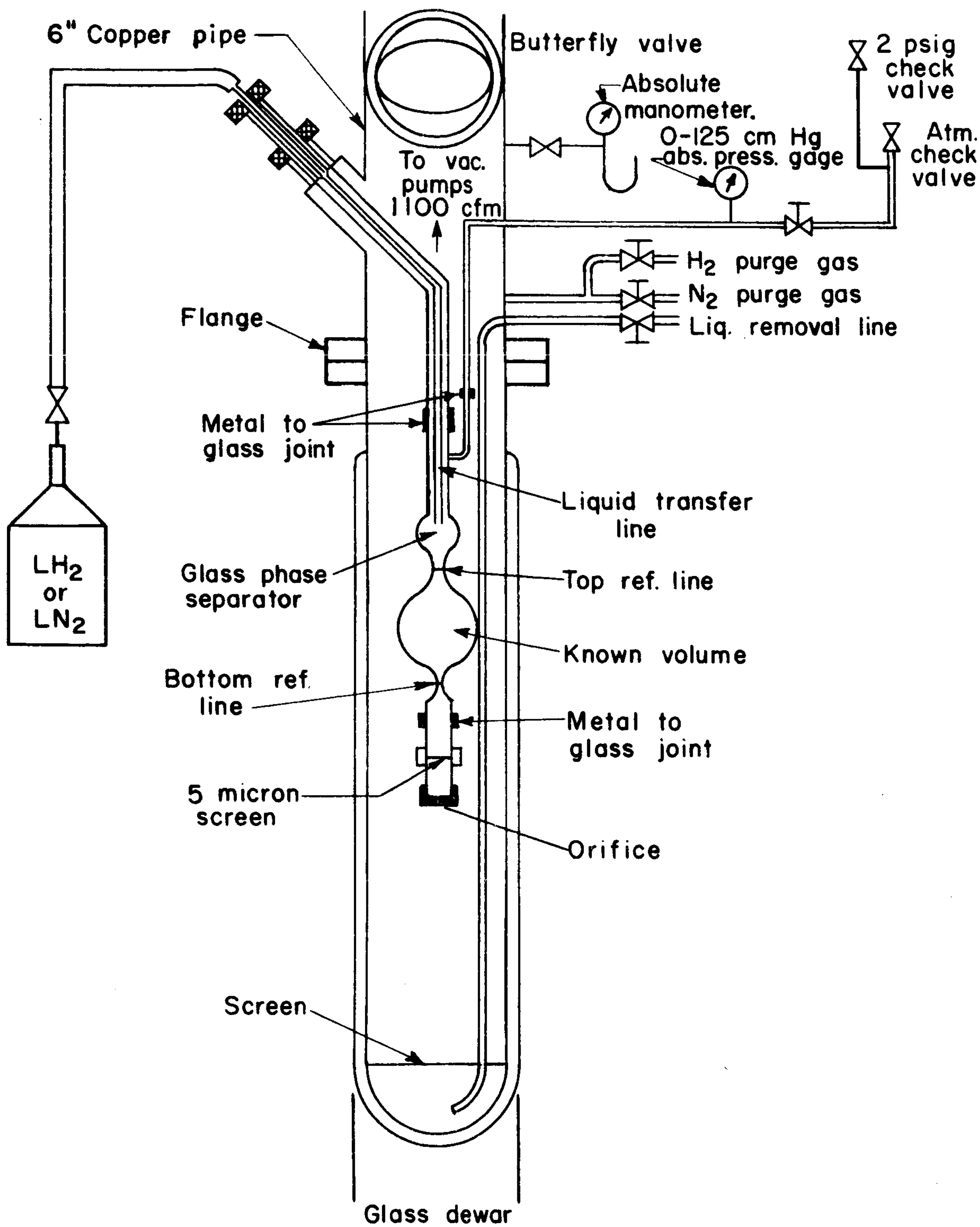

Fig. 1 Schematic diagram of apparatus for investigating cryogenic propellant flow characteristics.

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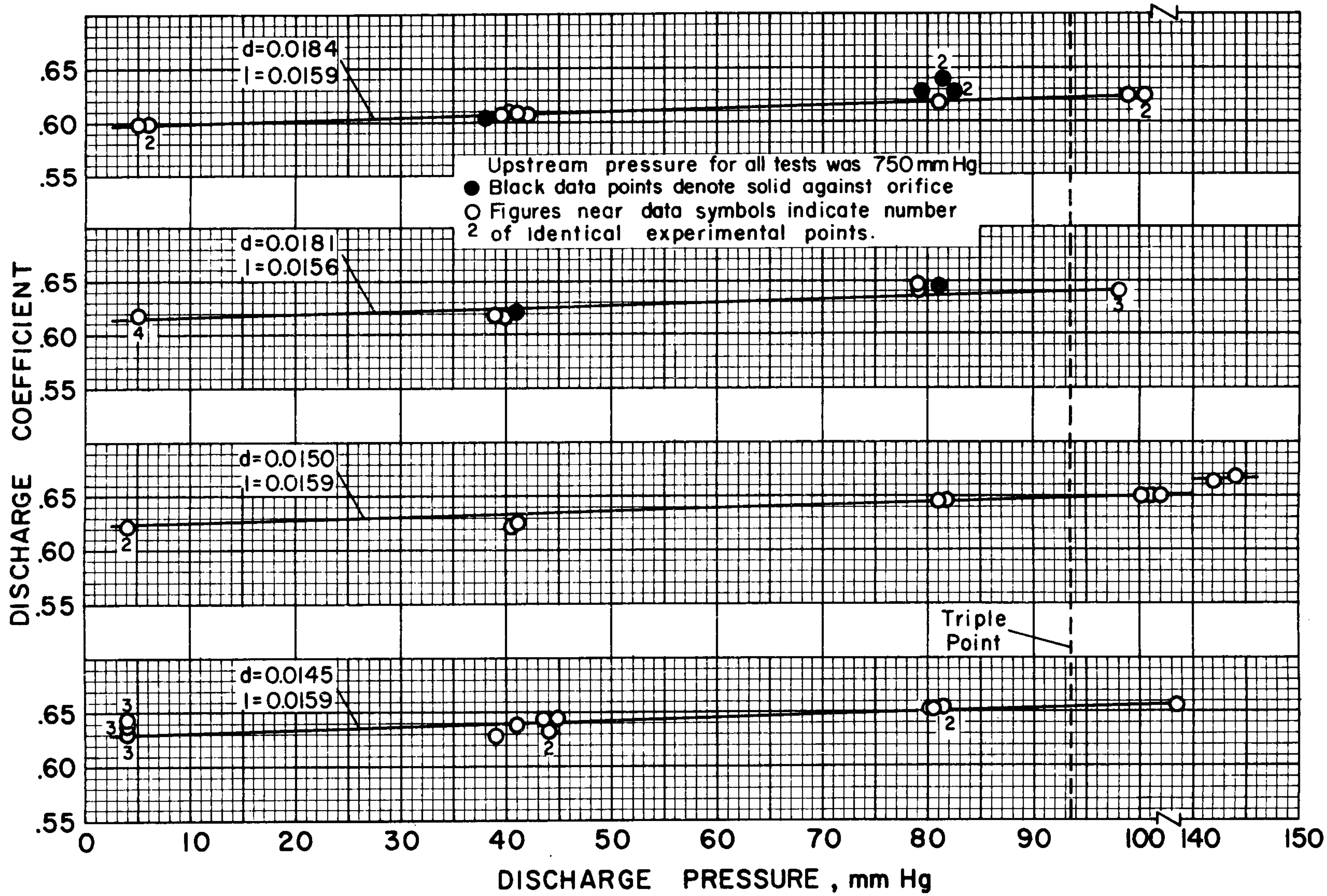

Fig. 2 Discharge coefficients for liquid nitrogen.

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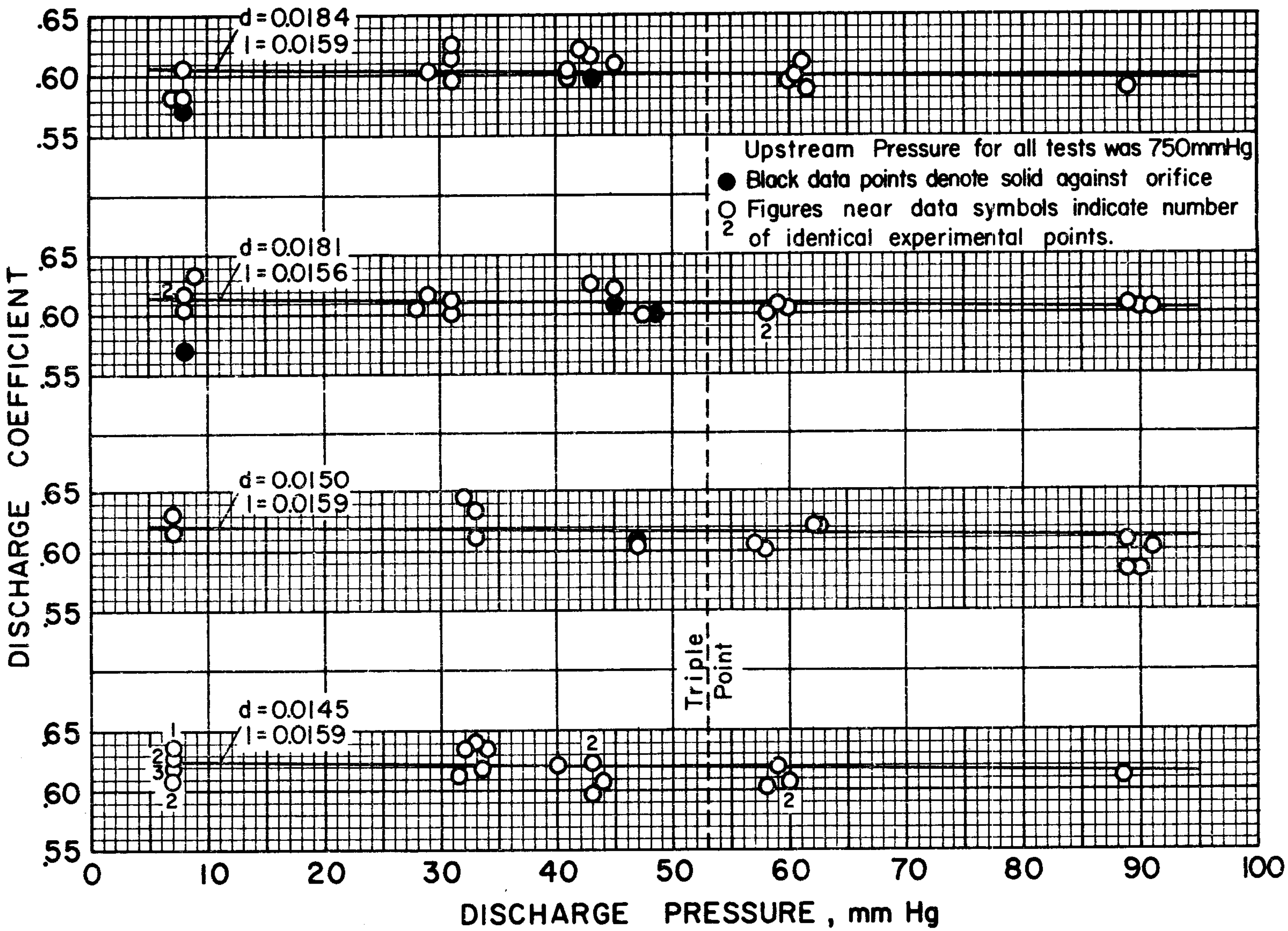

Fig. 3 Discharge coefficients for liquid hydrogen.

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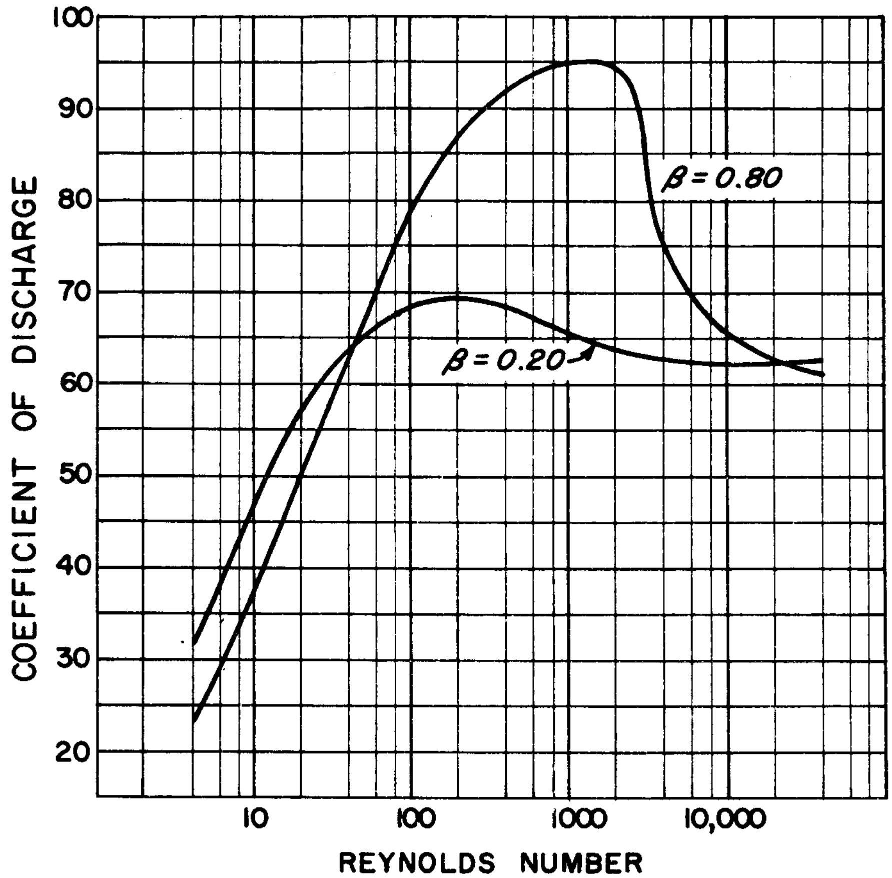

Fig. 4 Discharge coefficients from Tuve and Sprenkle (11).

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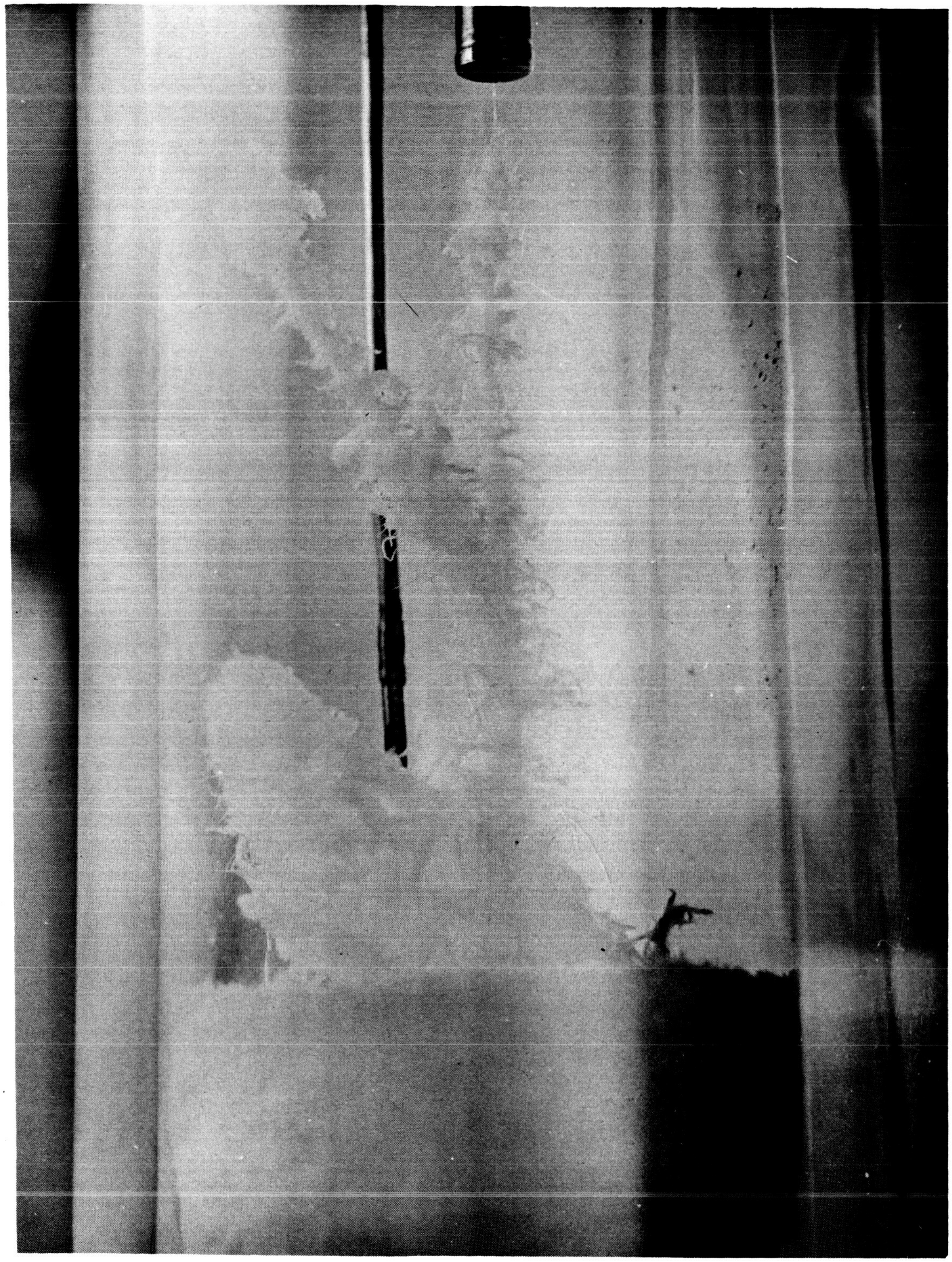

Fig. 5 Typical solid nitrogen formation at an intermediate discharge pressure.

Fig. 6 Typical solid nitrogen formation at an intermediate discharge pressure showing how solid builds up onto orifice.

Fig. 7 Typical solid nitrogen formation just below the triple point.